NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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EFFECTS OF ICE FORMATIONS ON AIRPLANE PERFORMANCE IN LEVEL CRUISING FLIGHT

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SUMMARY

A flight investigation in natural icing conditions was conducted by the NACA to determine the effect of ice accretion on airplane performance.

The maximum loss in propeller efficiency encountered due to ice formation on the propeller blades was 19 percent. During 87 percent of the propeller icing encounters, losses of 10 percent or less were observed. Ice formations on all of the components of the airplane except the propellers during one icing encounter resulted in an increase in parasite drag of the airplane of 81 percent. The control response of the airplane in this condition was marginal.

INTRODUCTION

The lack of quantitative evidence of the deleterious effects of ice formation on airplane components has restricted the evaluation of the icing problem and has therefore tended to retard the development and the adoption of new and improved ice-protection systems. Although serious reductions in airplane performance have often been experienced, possible errors in airspeed indications due to ice on the pitot static tube made difficult an accurate evaluation of the magnitude of the hazard; and the relative effects of ice on the propeller compared with that on the remainder of the airplane were not accurately evaluated.

Several investigations have been made of the effects of propeller icing (references 1 and 2), but very little research has been performed to determine quantitatively the effects of ice on other components.

Results of wind-tunnel investigations using simulated ice formations on propellers (reference 1) indicated a loss in propeller efficiency of only 3 percent for level-flight operating conditions. Propeller-whirl studies conducted by the Army Air Forces, during which icing conditions were artificially created, indicated negligible losses. In both cases the results were inconclusive because the quantities of ice simulated or obtained were smaller than formations frequently observed during flight in natural icing conditions.

Preliminary flight investigations of propeller icing in natural icing conditions (reference 2) indicated significant propeller performance losses. These data were inconclusive because they did not permit a distinction between the effects of propeller ice and the effects of ice formations on other components of the airplane.

An investigation was therefore undertaken to determine the effects of ice formations on propellers, wings, empennage, engine cowlings, and miscellaneous unprotected components of the airplane. Flight operations were conducted in the Great Lakes region by NACA Cleveland laboratory personnel and over most of the United States by the NACA Ames laboratory personnel under conditions of natural icing during the winter of 1946-47.

The degree of propeller unbalance experienced during flight with ice accretion on the blades was evaluated. Ice formations on the airplane were photographed to permit future simulation for aerodynamic studies in wind tunnels.

Special weather forecasting for the icing flights was provided by the United States Weather Bureau.

APPARATUS

The flight investigation by the Cleveland laboratory was conducted with a twin-engine airplane (fig. 1). This airplane was originally used by the Army Air Forces in the preliminary investigation of propeller icing reported in reference 2. The ice-prevention equipment provided by the manufacturer consists of a thermal heated-air system that protects the outboard wings, the horizontal and vertical tail surfaces, and the windshields. For this investigation, the anti-icing system was augmented by thermal electric anti-icing equipment for the fuselage foresection, the propellers, the inboard wings, the cowlings, and the antenna masts. Liquid-water content, droplet size, and droplet-size distribution were determined by means of rotating cylinders. The installation of the rotating cylinders and a disk-type icing-rate meter is shown in figure 2. The principles of operation of these instruments are explained in references 3 and 4. Special research equipment installed in the airplane is listed in table I.

The effects of ice on propeller performance were also obtained by the Ames laboratory with the C-46 airplane described in reference 5. Meteorological data were taken in the same manner as at the Cleveland laboratory.

PROCEDURE

Cleveland Laboratory

In order to determine the effects of ice formations on propellers, flights were conducted in clear-air conditions to establish the performance of the airplane without ice accretion. Performance data were then taken during flight in icing conditions. During nine of these flights, ice was allowed to collect only on the propellers and miscellaneous unprotected protuberances (loop antennas, antennas, and so forth) of the airplane. Performance data were also obtained in the icing conditions with ice removed from the propellers, but with ice accretions remaining on the miscellaneous protuberances.

In order to determine the effect of ice accretion on other components of the airplane, the propellers were anti-iced and the remainder of the airplane was allowed to ice. The respective performance loss attributed to ice formations on the wings, the empennage, the engine cowlings, and miscellaneous components was measured after selective de-icing of each component and noting the performance change of the airplane.

Rotating cylinders were exposed to icing conditions for at least one 5-minute period of each icing run. Free-air temperature and icing rate were continuously recorded during each run.

Performance data were reduced to standard conditions by the method described in reference 6. The parasite-drag increments due to icing of the airplane components other than the propeller were calculated and corrected for changes in induced drag and angle of attack.

Ames Laboratory

The investigation conducted at the Ames laboratory was limited to a study of the effects of ice on the propeller. The procedure was otherwise the same as at Cleveland, except that propeller thrust was measured by means of a thrust meter.

RESULTS AND DISCUSSION

Propeller Icing

The variation with indicated airspeed of the power required to maintain level flight for the twin-engine airplane used at the Cleveland laboratory with typical ice formations on the propellers is shown in figures 3 and 4. Calculated curves of power required with various losses in propeller efficiency are also included in order that the loss in propeller efficiency with ice accretion on the blades can be estimated. These data represent the maximum deleterious effects of glaze-ice and rime-ice formations on the propellers encountered during this investigation. With glaze-ice accretion, a heavy ice formation extended to approximately 30 percent of the blade radius and some deposits extended to 60 percent of the radius (fig. 3). The data for this condition indicate a loss in propeller efficiency of 7 percent, which is equivalent to a decrease in airspeed from 195 to 187 miles per hour at 1400 brake horsepower. During this icing encounter, another ice formation resulted in a propeller-efficiency loss of 17 percent. Such formations did not remain on the propellers for prolonged periods of time, however, because of natural shedding of ice from the blades.

Heavy rime-ice deposits extended to a 50-percent radius (fig. 4). Some small accretions adhered beyond the 50-percent radius. A loss in propeller efficiency of 12 percent resulted from this formation.

Seven other icing encounters resulted in smaller propeller-efficiency losses. These data are summarized in table II.

The maximum propeller unbalance encountered during this investigation was 85 ounce-inches. Vibrations were noted only when the unbalance exceeded 70 ounce-inches. Ice shedding from the propellers resulted in denting of the fuselage but no serious damage to the airplane structure existed. In one instance, ice thrown from the propellers penetrated the fuselage skin and caused some damage to interior equipment.

The results of the investigation indicate that the formation of ice on an airplane propeller will cause a significant reduction in airplane performance when certain meteorological conditions exist. The nine flights from the Cleveland laboratory, in conditions that varied from trace to light icing, were not sufficient to define the type of meteorological condition that produces the most deleterious effects on propeller performance. Some correlation between the icing rate and the propeller-efficiency loss was obtained, however, as shown in table II.

Data from the flight investigation at the Ames laboratory to determine the effect of ice formation on propeller performance are presented in table III. Only data that were sufficiently complete to be of interest are included in this table. The maximum loss in propeller efficiency was 19 percent, which is in agreement with the results presented in table II. During many of the flights, negligible losses in propeller efficiency were encountered.

A statistical study was made of data from both the Cleveland and Ames investigations to determine the most frequent loss in propeller efficiency encountered in 47 icing conditions. These data are presented in figure 5 and indicate that for approximately 8 percent of the icing encounters a loss in propeller efficiency of 15 to 20 percent was measured; 5 percent of the time, 10 to 15 percent; 50 percent of the time, 5 to 10 percent; and 37 percent of the time, 0 to 5 percent.

Component Icing

One flight at Cleveland was made to determine the effect on airplane performance of ice accretions on components of the airplane other than the propeller. The time history of the icing condition shown in figure 6 indicates that the average icing rate was approximately 4 inches per hour and that a maximum icing rate of approximately 12 inches per hour existed for a fraction of a minute. A comparison of the rotating-cylinder data with the icing-rate data for the corresponding period indicated that the average liquid-water content was approximately 0.4 gram per cubic meter with an average droplet diameter of 17 microns. These meteorological conditions are almost equal to the severest conditions that might be encountered in a stratus cloud as determined by reference 7.

Photographs of the resulting ice formations are shown in figures 7 to 13. Front and side views of the ice formation on the loop-antenna housing are shown in figure 7. Equally heavy ice collected on the antenna mast and on instrument-landing-system receiving antennas (fig. 8). Ice on the nose of the airplane was photographed on the ground after 15 minutes of flight in temperatures above freezing (fig. 9). Thin, rough, glaze-ice deposits extended well beyond the principal ice accretion. Several large isolated pieces indicate that the total formation was much larger during the flight. Ice on the leading edge of the engine cowling (fig. 10) was uniform but noticeably smaller than ice formations on the other components of the airplane. The ice formations on the inboard-wing panels were relatively small (fig. 11). The size of the formation can be judged by the 1-inch reference stripes on the wing surface. Some ice was lost from the outboard-wing panels (fig. 12), which was probably caused by the air loads on the ice and wing flexure. The photograph of the ice on the horizontal stabilizer (fig. 13) indicates the severity of the icing condition and the shape of the ice formation. Figure 13 also shows that some ice was lost because of air loads and flexure. 876

De-icing the components in the following order resulted in the corresponding changes in indicated airspeed at 1400 brake horsepower: inboard-wing panel, 163 to 166 miles per hour; tail surfaces, 166 to 170 miles per hour; outboard-wing panels, 170 to 182.5 miles per hour; engine cowling, 182.5 to 187 miles per hour; and miscellaneous components, 187 to 204 miles per hour. (See fig. 14.)

These data were interpreted in terms of parasite drag and are shown in figure 15 in percentage of total drag of the ice-free airplane. A drag increase of 8 percent was produced by ice accretion on the inboard-wing panels; empennage, 11 percent; outboard-wing panels, 27 percent; engine cowlings, 10 percent; and miscellaneous components, 25 percent.

This investigation did not include the determination of such factors as stalling speed, minimum single-engine speed, and low-speed flying qualities. It is significant that the control response of the airplane approached the point of being marginal when all of the airplane except the propeller had accreted ice.

SUMMARY OF RESULTS

From a flight investigation to determine the effect of ice formations on airplane performance in level cruising flight, the following results were obtained:

1. The maximum loss in propeller efficiency due to ice formation on the propeller blades in trace-to-light-icing conditions was 19 percent.

2. During this investigation, 87 percent of the icing encountered resulted in propeller-efficiency losses of 10 percent or less due to ice formation on the propeller blades.

3. Ice formations on all of the components of the airplane, except the propellers during one icing encounter, resulted in an increase in parasite drag of the airplane of 81 percent. The control response of the airplane in this condition was marginal.

4. The maximum propeller unbalance due to ice formations on the propeller blades was 85 ounce-inches.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 12, 1947.

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1. Corson, Blake W., Jr., and Maynard, Julian D.: The Effect of Simulated Icing on Propeller Performance. NACA TN No. 1084, 1946.

2. Kanter, M.: Flight Performance on XB-25E Airplane No. 42-32281 in Natural Ice During February, March and April 1945. AAF TR No. 5403, Air Materiel Command, Army Air Forces, Dec. 17, 1945. (Available from Office of Technical Services, U. S. Dept. of Commerce, as PB No. 27065.)

3. Anon.: The Multicylinder Method. The Mount Washington Observatory Monthly Research Bulletin, vol. II, no. 6, June 1946.

4. Vonnegut, B., Cunningham, R. M., and Katz, R. E.: Instruments for Measuring Atmospheric Factors Related to Ice Formation on Airplanes. M.I.T., De-Icing Res. Lab., April 1946. (Available from Office of Technical Services, U. S. Dept. of Commerce, as PB No. 48074.)

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6. Reed, Albert C.: Airplane Performance Testing at Altitude. Jour. Aero. Sci., vol. 8, no. 4, Feb. 1941, pp. 135-150.

7. Lewis, William: A Flight Investigation of the Meteorological Conditions Conductive to the Formation of Ice on Airplanes. NACA TN No. 1393, 1947.

TABLE I - APPARATUS USED IN FLIGHT INVESTIGATION BY CLEVELAND LABORATORY

	Equipment or instrument type	Accuracy
Propeller	Three blades; diameter, 12.5 ft; blade type, SPA-9, hub type, 5328-D12	
Propeller-blade angle	Slide-wire resistance element	$\pm 0.40^{\circ}$
Propeller vibration	Special vibrometer designed by Army Air Forces, which records vibrations of propeller order	±5 oz-in.
Engine power	Hydraulic piston-type torquemeter	±2 percent
Airspeed	Sensitive indicator; fuselage static orifices corrected for position error; heated total head	1 percent
Altitude	Sensitive-type altimeter; fuselage static orifices corrected for position error	1 percent
Engine speed	Sensitive-type tachometer	1 percent
Fuel flow	Reaction-type flowmeter	±5 lb/hr
Air temperature	Resistance-bulb thermometer shielded for radiation and impingement of water and ice	1° dry-air calibration
Liquid-water content, droplet size, and type of distribution	Rotating cylinder $\frac{1}{8}$-, $\frac{1}{2}$-, $1\frac{1}{4}$-, and 3-in. diameter, located on top rear section of fuselage (fig. 2); principle explained in references 4 and 5	±0.02 g/cu meter
Icing rate	Rotating-disk meter, 2-in. diameter × $\frac{1}{32}$ in. (fig. 2); principle explained in reference 4	±0.05 in./hr
Propeller photographs	Type D-1 flash unit synchronized with propeller and 4 × 5 in. camera to enable photographing any blade in upright position	
Electrical power supply for anti-icing	62.5 kv.-a. 3-phase, 208-volt, auxiliary-power unit	

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TABLE II - CLEVELAND LABORATORY PROPELLER-ICING DATA

Average propeller speed (rpm)	Propeller-blade angle (deg)	Pressure altitude (ft)	Free-air temperature (°F)	Liquid-water content (g/cu m)	Average droplet diameter (microns)	Drop-size distribution	Type of ice	Icing rate (in./hr)	Airspeed loss at 1400 bph (mph)[a]	Propeller-efficiency loss (percent)	Propeller unbalance (oz/in.)
1010	31.2-33.4	11,040	21	0.18	24	E	Glaze	2.3	17	17	74
1040	Fixed at 34.1	9,000	15	.17	20	A	Rime	2.8	13	12	85
1050	Fixed at 34.1	6,200	19	.19	18	A	Rime	1.6	8	7	70
1100	Fixed at 32.5	3,600	-4	.17	9	A	Rime	1.5	8	6	45
1100	Fixed at 32.8	4,000	0	.14	12	E	Rime	1.2	9	8	---------
1070	Fixed at 34.1	7,400	10	.18	12	A	Rime	.6	6	4	---------
1070	31.7-32.7	3,370	14	.15-.30	6-8	E	Rime	.5	2	2	75
1000	Fixed at 35.0	3,700	-4	.17	9	A	Rime	.4	6	5	45
1010	31.8-32.5	5,750	2	.06	12	A	Rime	----------	6	5	---------
Vary	Variable	5,900	-15	--------	---------	---------	Dry	----------	--------	----------	---------
Vary	Variable	2,000 7,000	17 4	--------	---------	---------	Dry	----------	--------	----------	---------

[a]Corrected to standard gross weight and density conditions.

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TABLE III - AMES LABORATORY PROPELLER-ICING DATA

Average propeller speed (rpm)	Propeller-blade angle (deg)	Pressure altitude (ft)	Indicated airspeed (mph)	Free-air temperature (°F)	Liquid-water content (g/cu m)	Average droplet diameter (microns)	Propeller-efficiency loss (percent)
1050	23	4500-6000	170	22	--------	13	3.2
1040-1200	25	11,000	163	18	0.10	19	6.5
1100	22	5,100	163	18	.11	12	8.5
1150	21	5,100	163	18	.11	12	9.8
1060	25	11,000	170	20	.13	10	9.0
1050	26	11,700	170	24	.16	15	6.0
1050	27	11,500	177	24	.16	14	5.5
1100	----------	7,400	176	11	.18	23	6.0
1060	----------	7,400	164	11	.21	17	6.0
1100	----------	7,500	170	10	.21	35	7.5
1125	24	11,000	150-186	20	.21	12	8.0
1050	----------	19,700	149	-12	.22	23	0
1050	24	6,100	179	20	.22	10	4.0
1050	----------	5,100	147	22	.24	13	10.0
1050	----------	5,200	148	22	.29	13	5.0
1200	----------	6500-6900	160	11	.17-.44	13	6.0
1130	25	10,900	153	19	.41	13	6.0
1115	----------	11,000	165	24	.44	15	8.0
1050	23	5,100	---------	18	--------	---------	19.0
1100	25	11,510	---------	25	--------	---------	15.3

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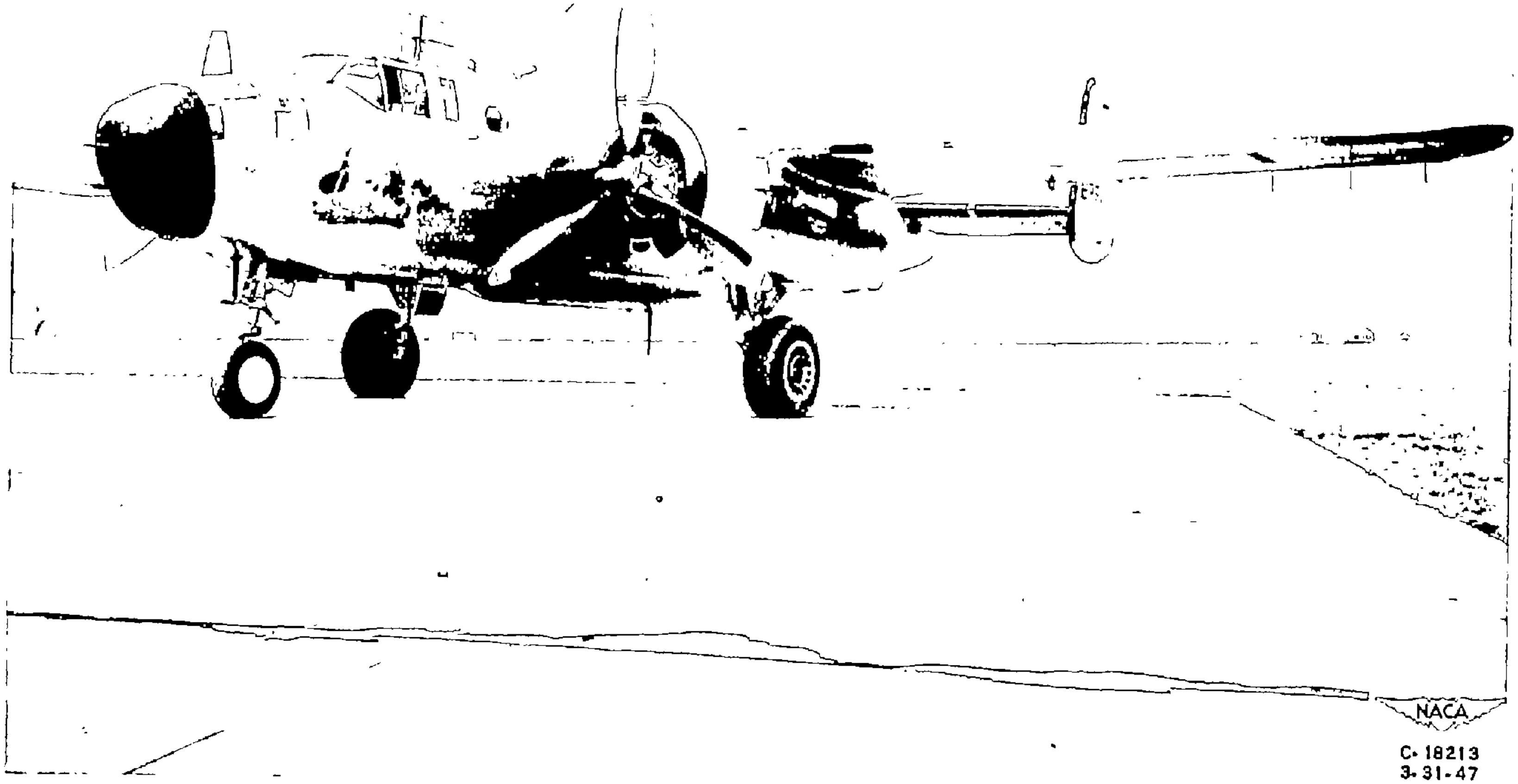

Figure 1. – Airplane equipped with thermal anti-icing on propellers, wings, empennage, cowling leading edge, fore section of fuselage, and miscellaneous antenna masts.

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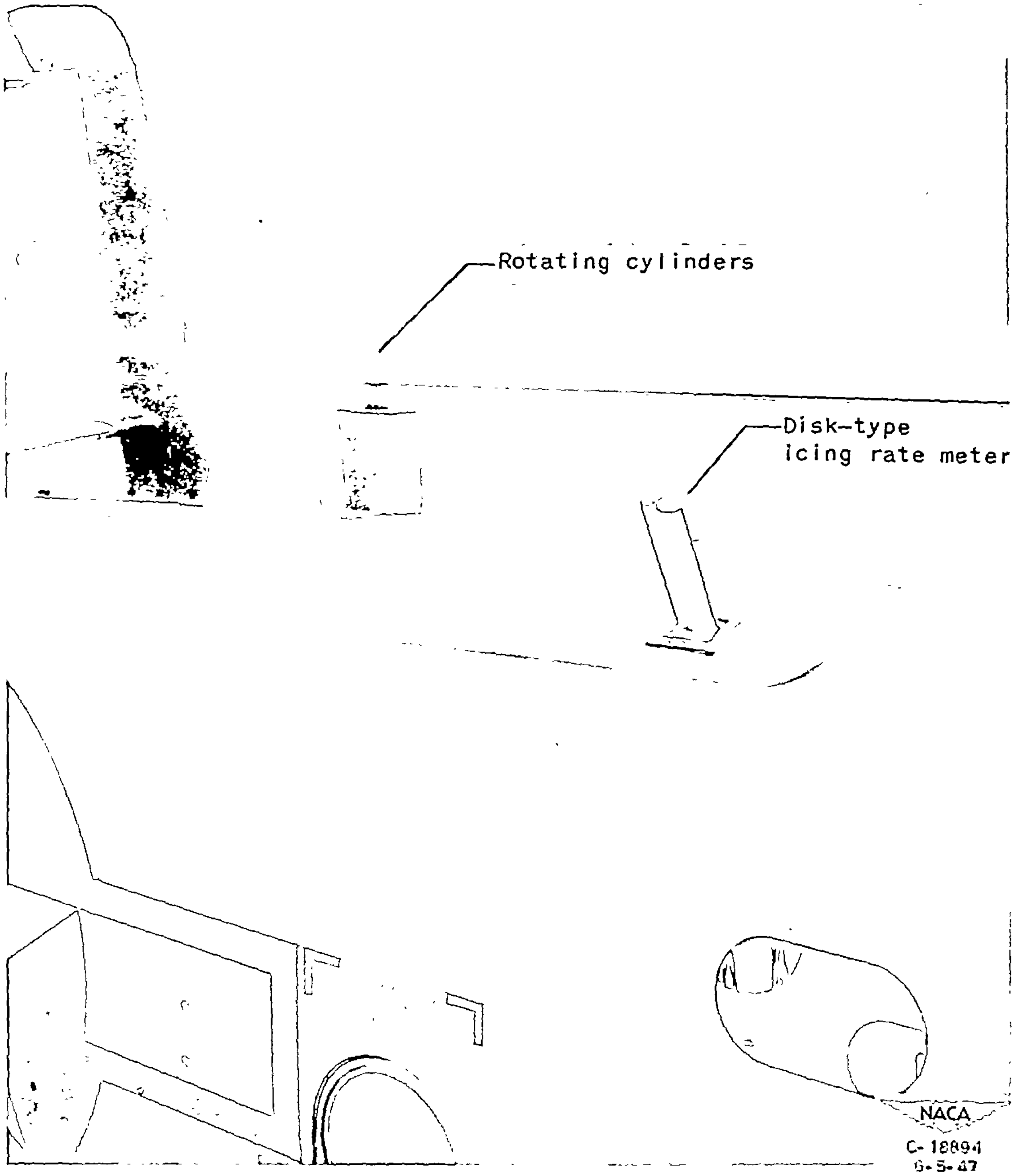

Figure 2. - Rotating-cylinder assembly and disk-type icing-rate indicator on top of airplane.

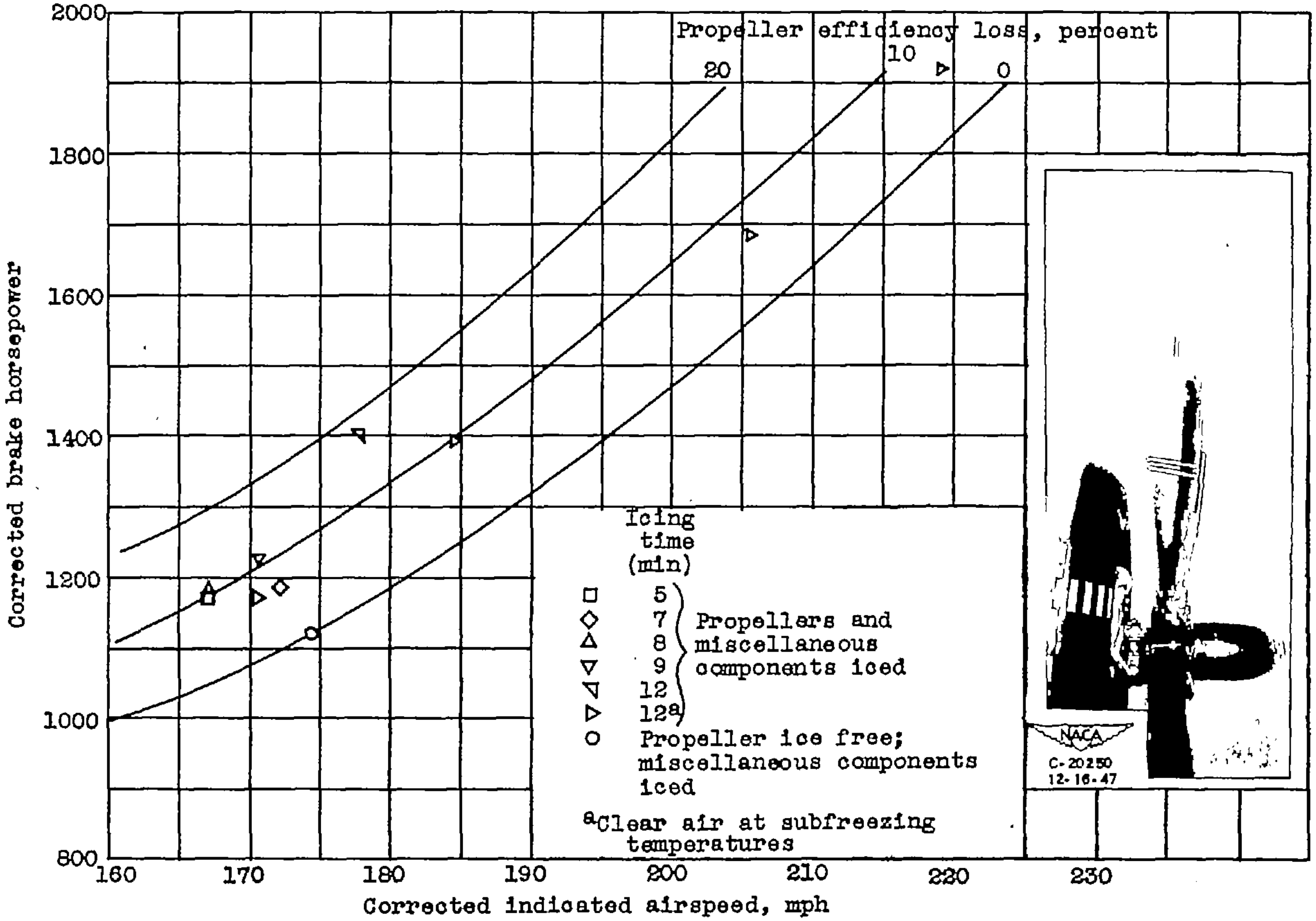

Figure 3. - Performance of airplane with ice-free propellers and with accumulations of glaze ice on propellers. Icing rate, 2.3 inches per hour.

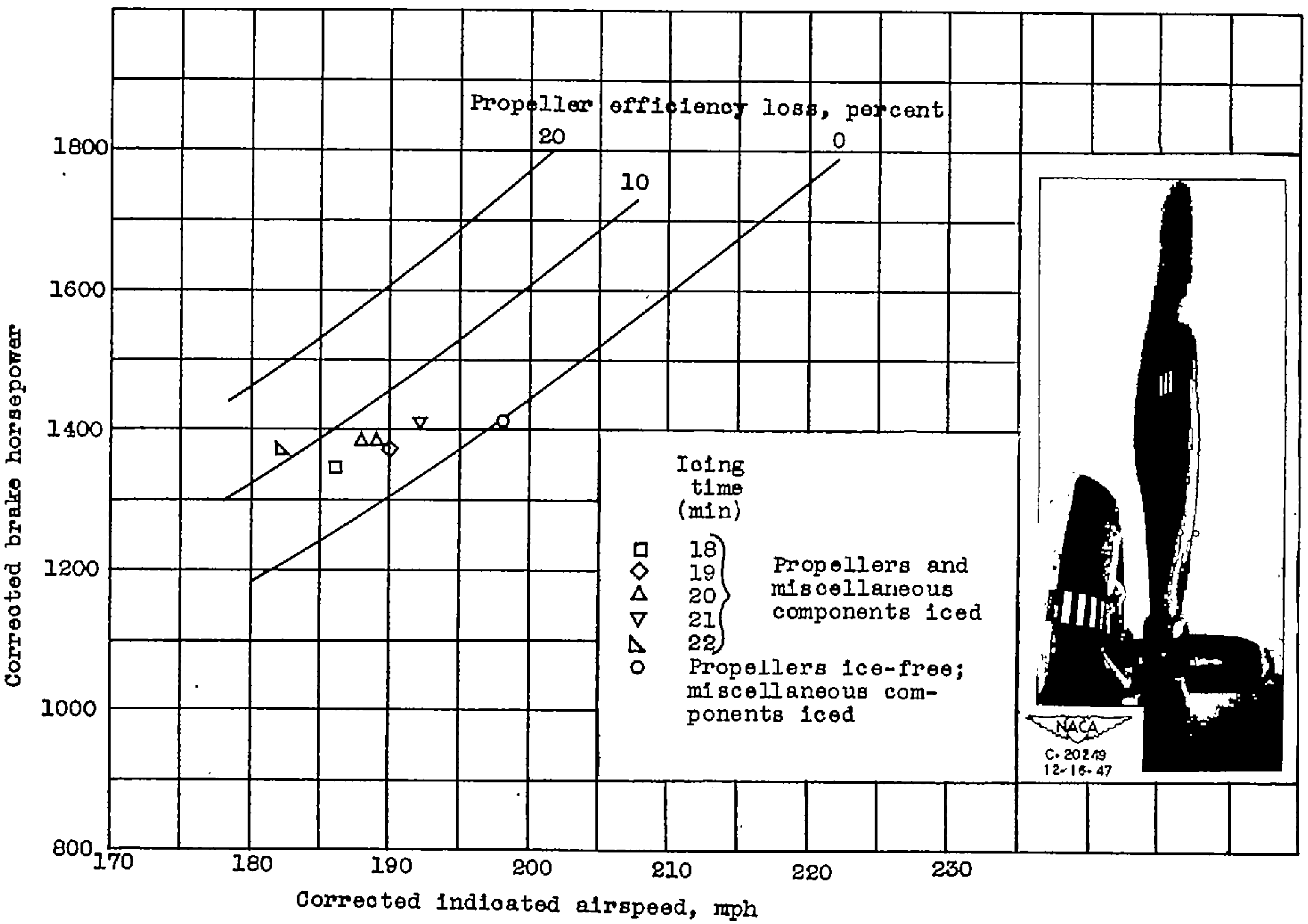

Figure 4. - Performance of airplane with ice-free propellers and with rime-ice accumulations on propellers. Icing rate, 2.8 inches per hour.

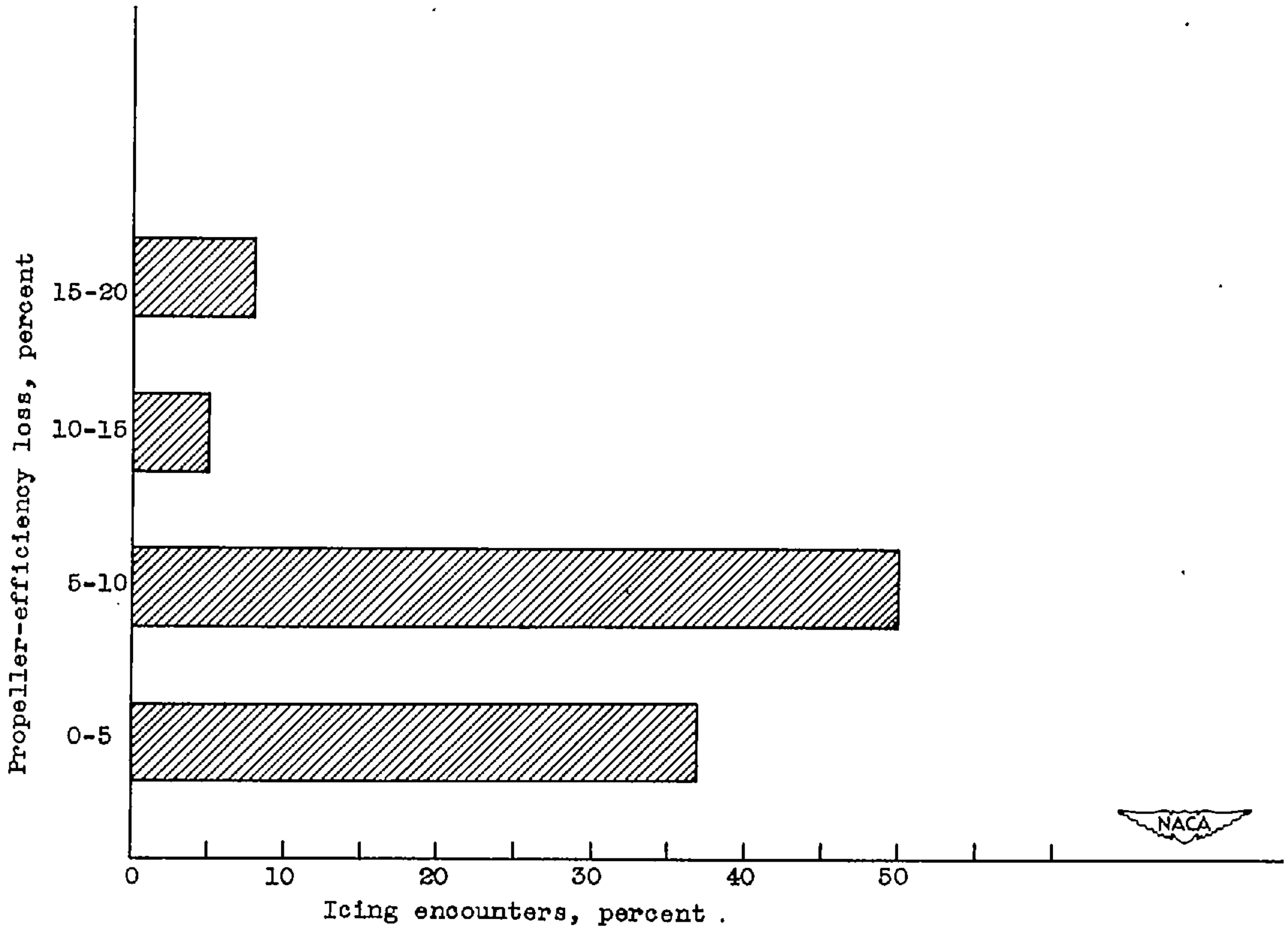

Figure 5. - Loss of propeller efficiency associated with frequency of icing encounters. (Cleveland and Ames laboratory data)

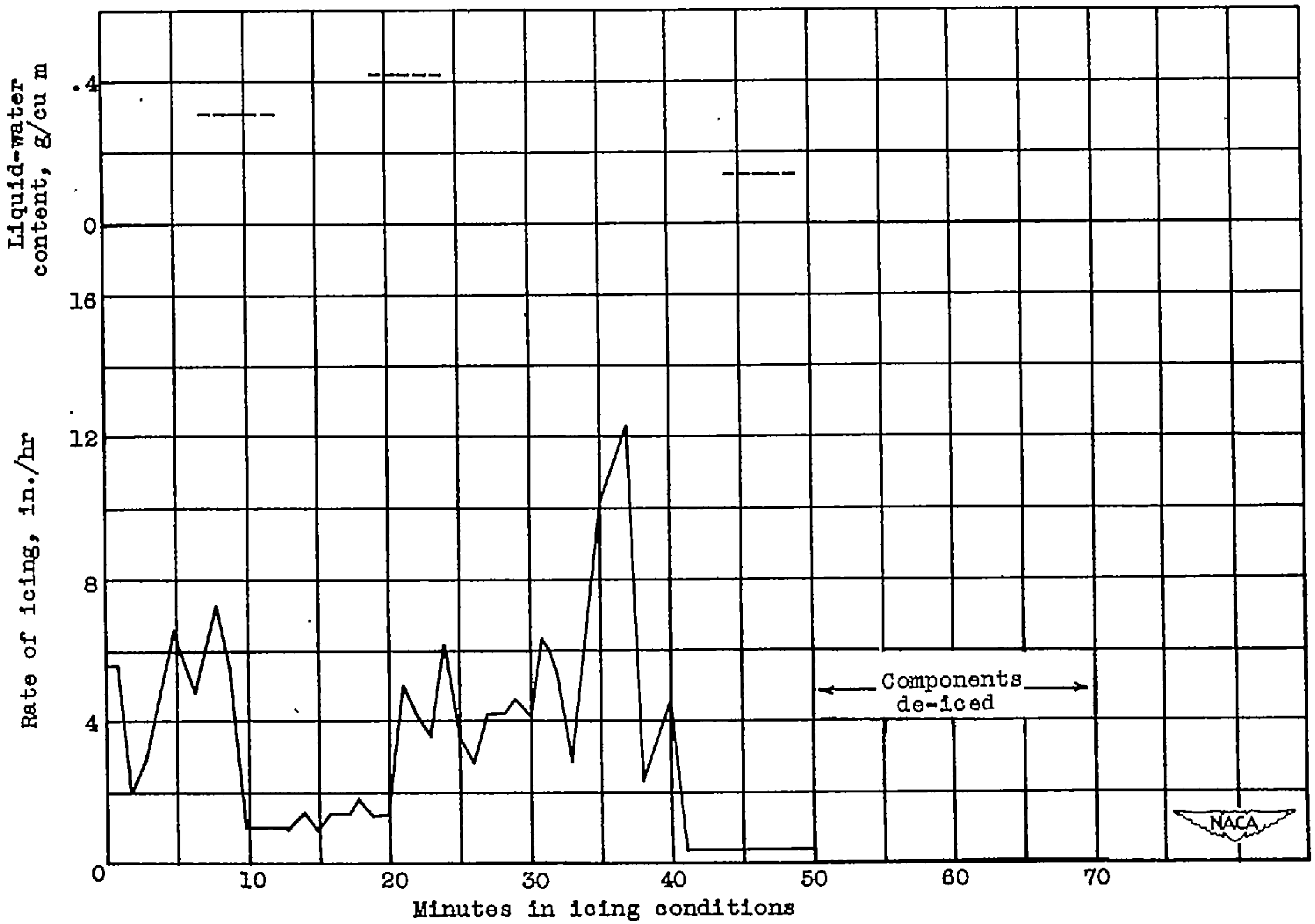

Figure 6. - Meteorological conditions during period while icing components of airplane.

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(a) Formation on loop antennae housing, front view.

(b) Formation removed from loop antennae housing, side view.

Figure 7. - Formation of ice accumulated on loop-antenna fairing. Average icing rate, 4 inches per hour; liquid-water content, 0.4 gram per cubic meter; droplet size, 17 microns.

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Figure 8. - Ice formation on antenna mast and instrument-landing-system receiving antennas. Average icing rate, 4 inches per hour; liquid-water content, 0.4 gram per cubic meter; droplet size, 17 microns.

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Figure 9. - Formation of ice on nose section of fuselage. Photograph taken on ground following flight through temperatures above freezing for 15 minutes. Average icing rate, 4 inches per hour; liquid-water content, 0.4 gram per cubic meter; droplet size, 17 microns.

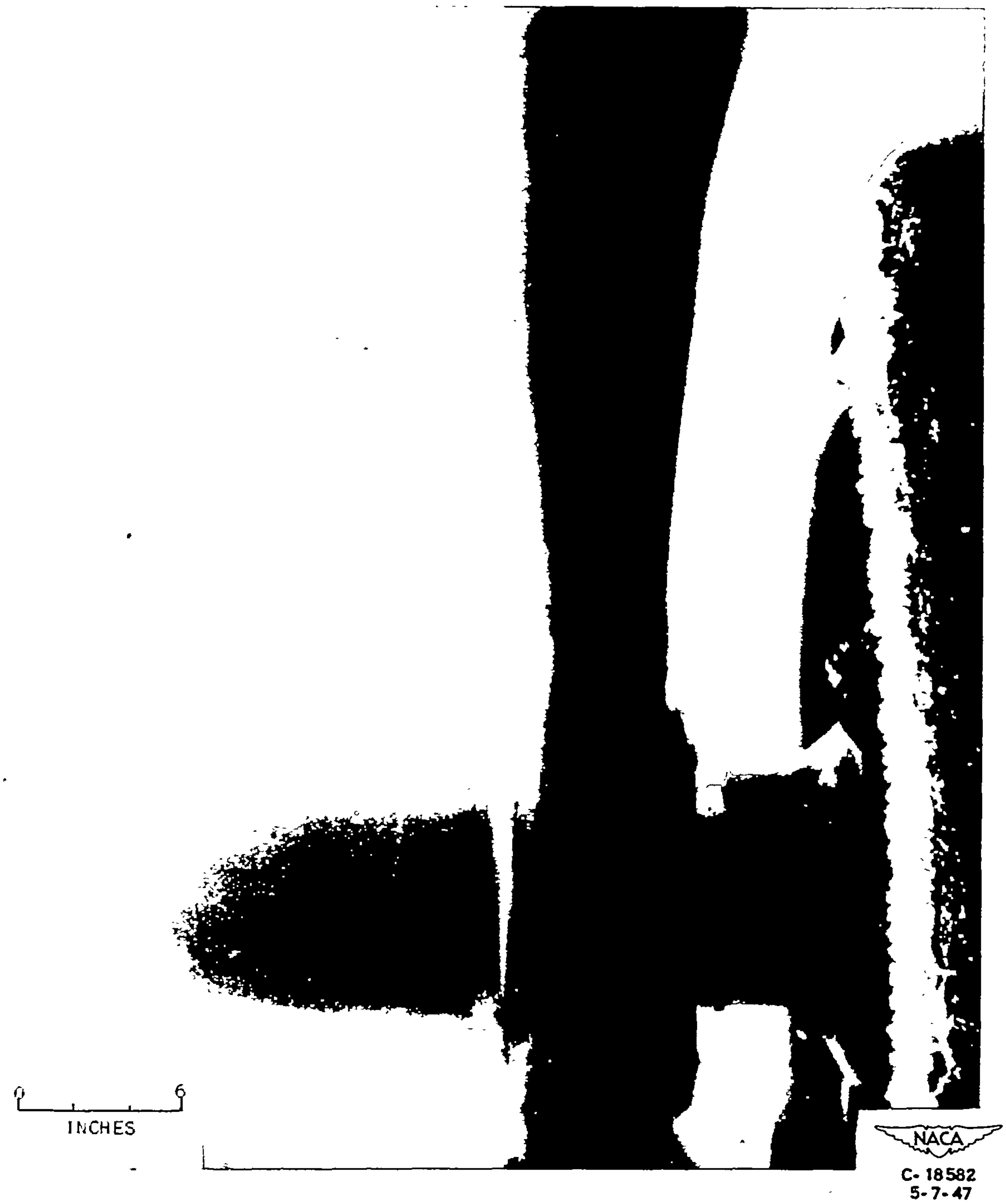

Figure 10. - Formation of ice on leading edge of cowling and spinner. Average icing rate, 4 inches per hour; liquid-water content, 0.4 gram per cubic meter; droplet size, 17 microns.

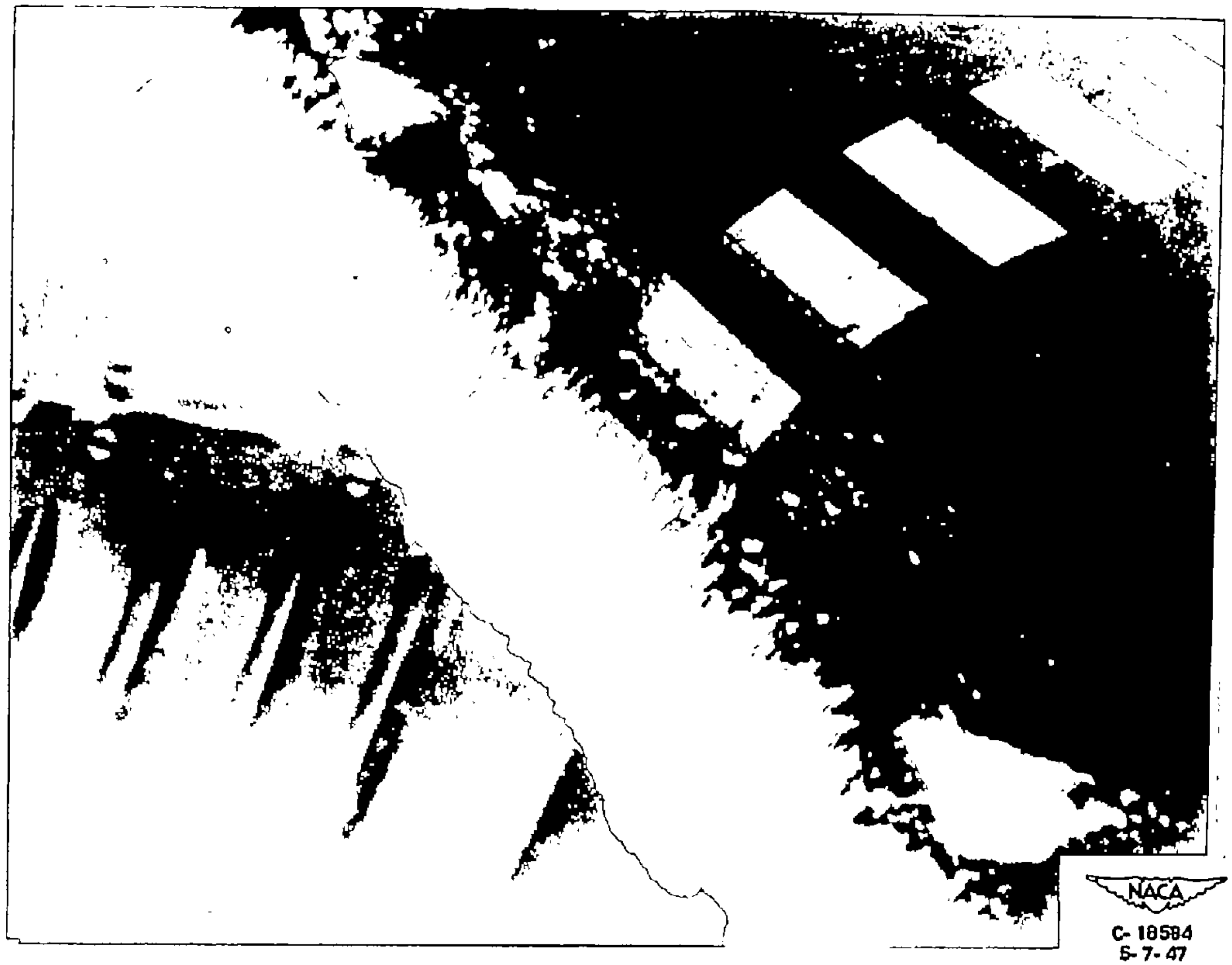

Figure 11. - Formation of ice on inboard-wing panel of airplane. Average icing rate, 4 inches per hour; liquid-water content, 0.4 gram per cubic meter; droplet size, 17 microns. (Painted stripes are 1 in. wide.)

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Figure 12. - Formation of ice on outboard-wing panel showing sections of ice lost by wing flexure. Average icing rate, 4 inches per hour; liquid-water content, 0.4 gram per cubic meter; droplet size, 17 microns. (Painted stripes are 1 in. wide.)

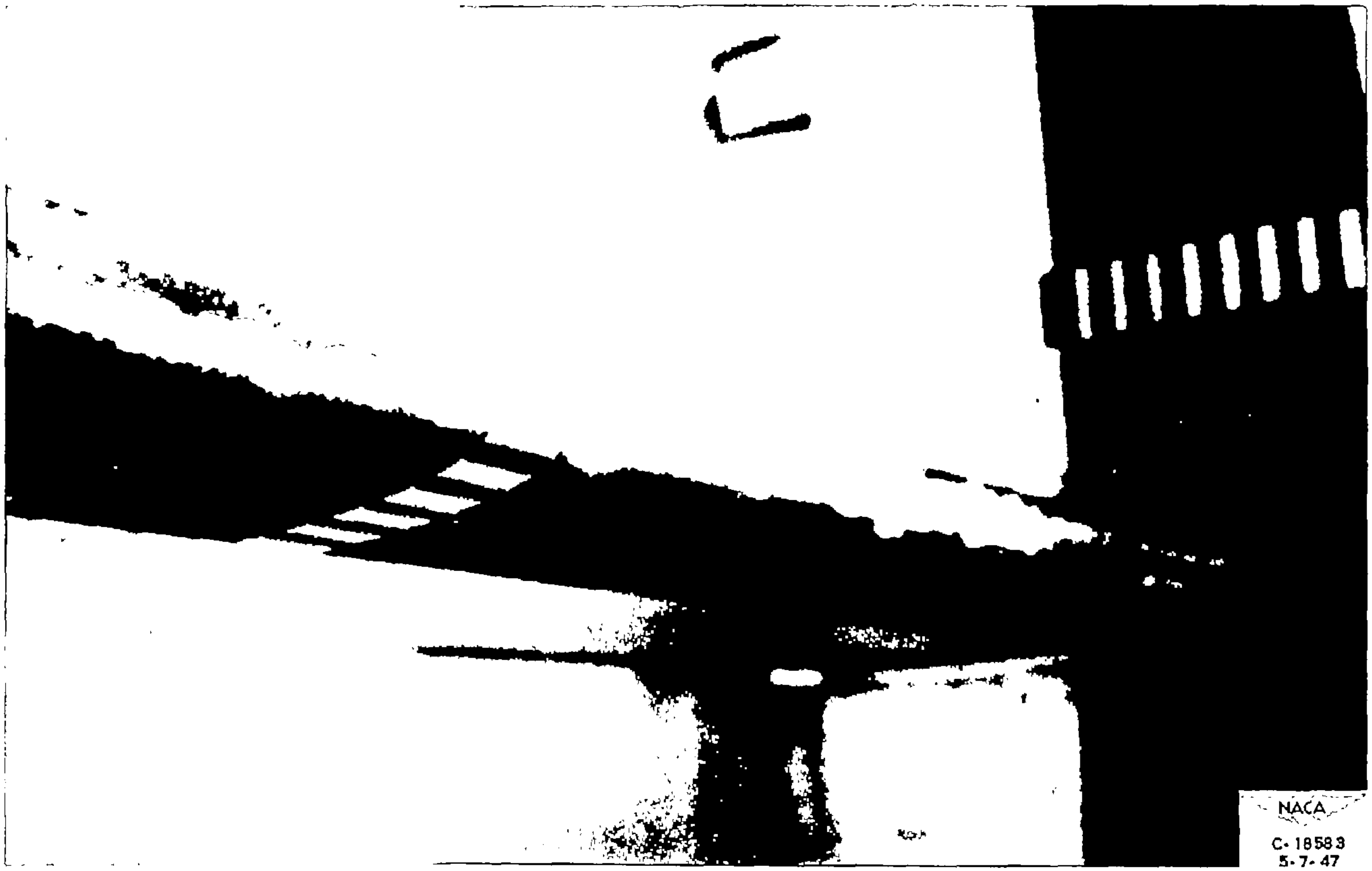

Figure 13. - Formation of ice on horizontal stabilizer. Average icing rate, 4 inches per hour; liquid-water content, 0.4 gram per cubic meter; droplet size, 17 microns. (Painted stripes are 1 in. wide.)

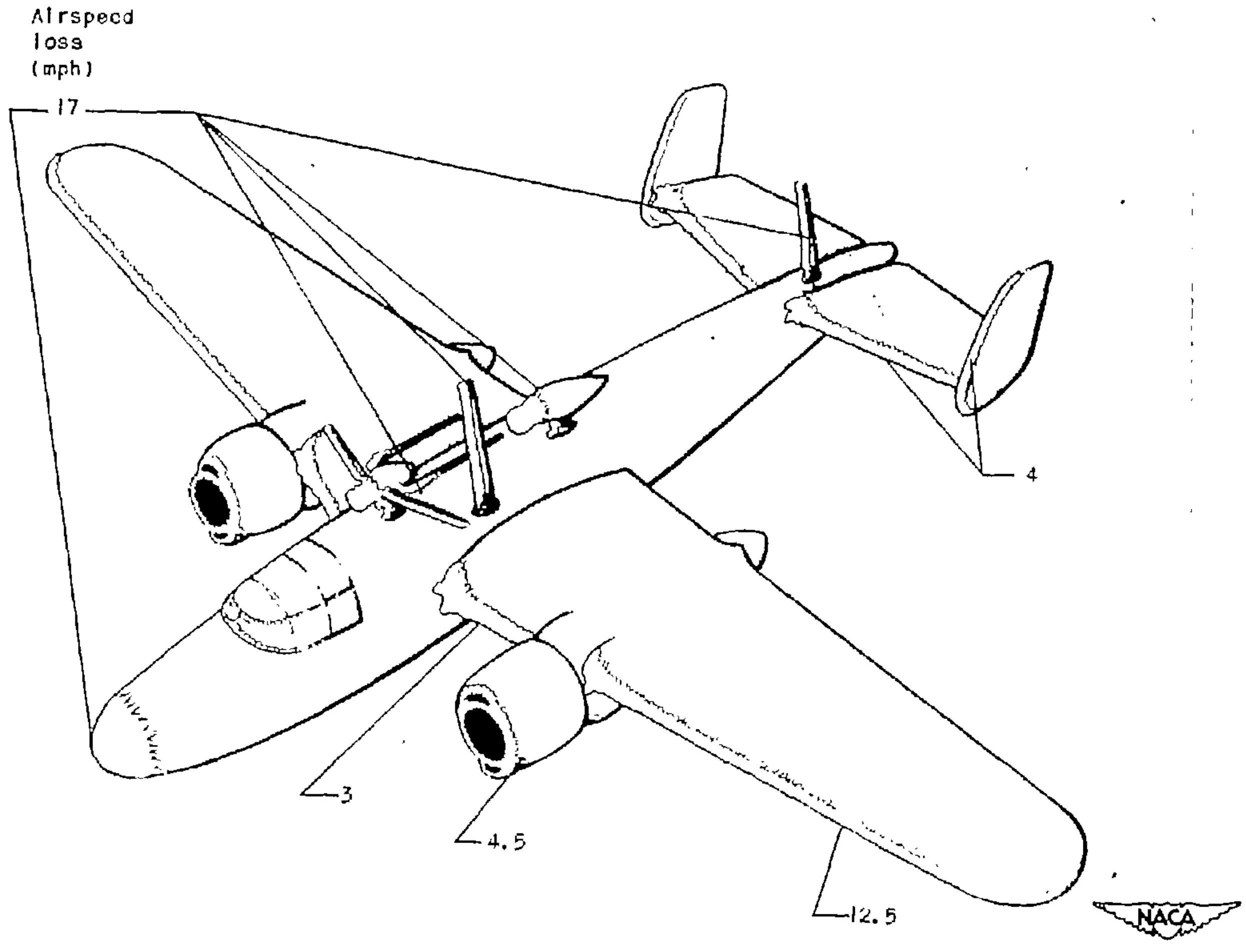

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Figure 14. - Airspeed loss caused by ice accumulations on various components of airplane. Total airspeed loss, 41 miles per hour, from 204 to 163 miles per hour.

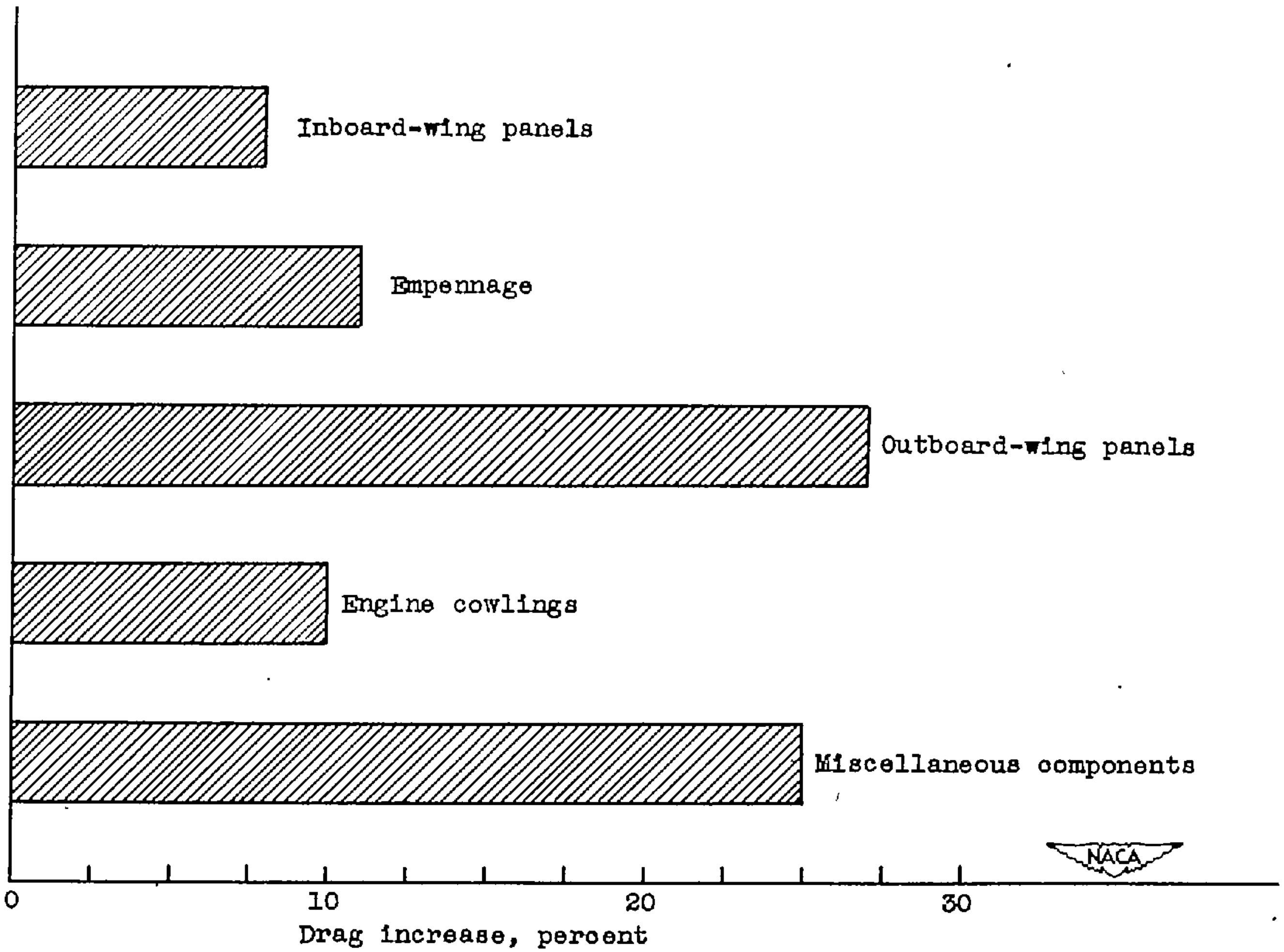

Figure 15. - Drag increase associated with icing of individual components of airplane.